CONSTRAINTS ON EXTRA GAUGE BOSONS IN $e\gamma$ COLLISIONS

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Abstract

We investigate the sensitivity of $e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$ to extra charged gauge bosons. The sensitivity is much below that of $e^-e^+ \to \nu\bar{\nu}\gamma$. We conclude that $e^-\gamma \to d\bar{u}\nu_e$ and $e^-\gamma \to f\bar{f}e^-$ are also inferior to e^+e^- collisions in setting bounds on extra charged and neutral gauge bosons and on four fermion contact interactions.

1. Motivation

Extra gauge bosons are predicted in many extensions of the Standard Model (SM). Constraints on these particles or their discovery would constrain theories extending the SM. Therefore, the search for extra gauge bosons is foreseen in the research program of every future collider.

In e^+e^- collisions, the process $e^+e^- \to \nu\bar{\nu}\gamma$ can constrain extra neutral (Z') and extra charged (W') gauge bosons together, while the processes $e^-\gamma \to d\bar{u}\nu_e$ and $e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$ in $e\gamma$ collisions could constrain extra charged gauge bosons independent of neutral gauge bosons.

We focus here on the process $e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$ because it has a clean signature and is free of QCD backgrounds. It is known to give interesting constraints on anomalous W couplings.[1]

Constraints on extra gauge bosons from $e^-\gamma$ collisions have to compete with present and future constraints from other experiments, especially with those from e^+e^- collisions. It has been shown[2,3,4] that the process $e^+e^- \to \nu\bar{\nu}\gamma$ can put limits on extra charged gauge bosons. For $\sqrt{s} = 0.5\,TeV$, $L_{int} = 500\,fb^{-1}$ and neglecting systematic errors, one is sensitive[4] to a W' with a mass of $1.2\,TeV$–$4.6\,TeV$ depending on the model. These limits degrade to $0.6\,TeV$–$1.8\,TeV$ if a systematic error of 2% is included for the observed cross sections.

2. Calculation

To lowest order, the process $e^-\gamma \to \mu^-\nu_e\bar{\nu}_\mu$ is described by the Feynman diagrams shown in figure 1. We performed two independent calculations of the cross
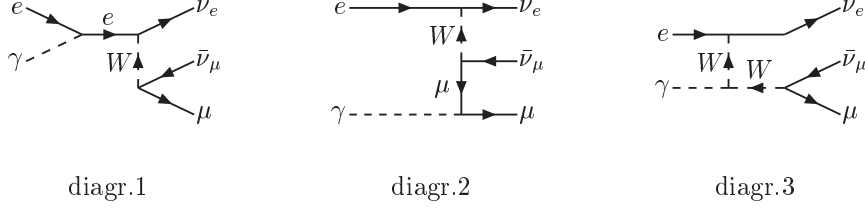
diagr.1   diagr.2   diagr.3

Fig. 1 *The lowest order Feynman diagrams for the process $e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$.*

section. In one calculation, the squared matrix element is obtained by usual trace techniques with the help of the symbolic manipulation program `form`,[5] and integrated analytically over the phase space. The remaining integrations are done by an adaptive Simpson routine. In the other calculation, helicity amplitudes are calculated by spinor techniques[6] and then squared analytically. The integration over the squared matrix element is performed by the MC method. Both calculations agreed with CompHEP[7] for the SM with unpolarized beams. They also agreed with each other for extensions of the SM.

For completeness, we present here the formula for the squared amplitude. The generalized couplings may be inferred from the $W_i l\nu$ vertex

$$W_i l\nu = \frac{ig}{\sqrt{2}}\gamma^\mu \left(\frac{1-\gamma_5}{2}\, a_i + \frac{1+\gamma_5}{2}\, b_i \right). \tag{1}$$

We have $a_1 = 1$, and $b_1 = 0$ in the SM.

In order to present the result for the squared amplitude, $|\mathcal{M}(\lambda_e, \lambda_\gamma)|^2$ (dependent on the polarizations λ_e and λ_γ of the electron and the photon), in $e^-(p_-)+\gamma(p_+) \to \nu(q_-) + \bar{\nu}(q_+) + \mu^-(k)$, we first define the kinematic invariants:

$$
\begin{array}{llll}
s = & (p_+ + p_-)^2, & s' = & (q_+ + q_-)^2, \\
t = & (p_+ - q_+)^2, & t' = & (p_- - q_-)^2, \\
u = & (p_+ - q_-)^2, & u' = & (p_- - q_+)^2, \\
k_\pm = & 2p_\pm \cdot k, & k'_\pm = & 2q_\pm \cdot k, \\
W_i = & k'_+ - M_{W_i^2} + iM_{W_i}\Gamma_{W_i}, & W'_i = & t' - M_{W_i^2} + iM_{W_i}\Gamma_{W_i}.
\end{array} \tag{2}
$$

The resulting expression for $|\mathcal{M}(\lambda_e, \lambda_\gamma)|^2$ is then

$$|\mathcal{M}(L, L)|^2 = \frac{2(4\pi)^3\alpha^3}{s_W^4 s' s k_+} \sum_{\substack{i=1,n \\ j=i,n}} W_{ij}^+ \cdot (a_i^2 a_j^2 k'_-{}^2 + a_i a_j b_i b_j s'^2) \tag{3}$$

$$|\mathcal{M}(L, R)|^2 = \frac{2(4\pi)^3\alpha^3}{s_W^4 s' s k_+} \sum_{\substack{i=1,n \\ j=i,n}} W_{ij}^- \cdot (a_i^2 a_j^2 u^2 + a_i a_j b_i b_j k_-^2) \tag{4}$$

$$|\mathcal{M}(-\lambda_e, -\lambda_\gamma)|^2 = |\mathcal{M}(\lambda_e, \lambda_\gamma)|^2[a \leftrightarrow b, W_{ij}^\pm \leftrightarrow W_{ij}^\mp] \tag{5}$$

with

$$W_{ij}^\pm = (2 - \delta_{ij})\mathrm{Re}(F_i^\pm F_j^{\pm *}) \tag{6}$$

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and

$$F_i^\pm = \frac{s'}{W_i} + \frac{tt' + ss' - uu' \pm 4i\varepsilon_{\mu\nu\rho\sigma}p_-^\mu p_+^\nu q_-^\rho q_+^\sigma}{2W_i W_i'}, \tag{7}$$

where $\varepsilon_{\mu\nu\rho\sigma}$ is the completely antisymmetric Levi-Civita tensor and $\varepsilon_{0123} = 1$. The summation runs over the number, n, of charged gauge bosons in the theory ($n = 1$ in the SM and $n = 2$ in a theory with one W').

For numerical calculations, we use the physical input $M_W = 80.33\, GeV$, $\Gamma_W = 2.06\, GeV$, $\alpha = 1/128$, $\sin^2\theta_W = 0.23124$ and $m_\mu = 0$.

The massless muon does not lead to a divergent cross section because we apply the following cuts on the angle between the muon and the photon and on the muon energy,

$$10° < \theta(\gamma, \mu) < 170°, \quad E_\mu > 10\, GeV, \tag{8}$$

to ensure that the muon gives a signal in the detector. We assume 90% polarization of the electron and photon beams.

As observables, we consider different polarized and unpolarized cross sections,

$$\sigma, \; \sigma_{LU}, \; \sigma_{RU}, \; \sigma_{LL}, \; \sigma_{LR}, \; \sigma_{RL}, \; \sigma_{RR}. \tag{9}$$

The first (second) index refers to the electron (photon) helicity. In addition, we consider the distributions $d\sigma/dc$, $c = \cos\theta(\gamma, \mu)$ and $d\sigma/dE_\mu$. We assume a systematic error of 2% in these observables. Therefore, the W' must produce in these observables a deviation of at least 2% to give a signal.

We do not convolute over the photon energy spectrum here. We understand that this would be needed in a final calculation of the process. However, it would not change our main conclusions.

We present numerical results for different models containing extra charged gauge bosons. See reference[4] for a more detailed description of the models. Here is a short summary to make this paper self contained.

LRM: Left-right-symmetric model with $\kappa = g_R/g_L$, $\rho = 1(2)$ for symmetry breaking through Higgs doublets (triplets).

SSM: Sequential SM, the W' is a heavy repetition of the SM W, $a_2 = 1$, $b_2 = 0$.

SSM W_R': As the SSM, but with a right-handed W', $a_2 = 0$, $b_2 = 1$.

UUM: Un-unified model, quarks and leptons are gauged by different $SU(2)$ gauge groups, $G = SU(3)_c \times SU(2)_q \times SU(2)_l \times U(1)_Y$, characterized by a mixing angle, ϕ, which represents the mixing between the charged bosons of the two $SU(2)$ symmetries.

KK: Kaluza Klein excitations, here only the first excitation is considered. The corresponding W' couples as in the SSM but with fermionic couplings which are a factor $\sqrt{2}$ larger. The γWW coupling is unaffected since there is only the SM photon, which couples to charge as usual.

3. Results and Discussion

Figure 2 shows total cross sections for different beam polarizations and for different models. We see that the process has a cross section of several pb. Unfortunately, the deviation from the SM is very small for the considered models. It can be enhanced by right-handed polarized electrons and photons. However, the process
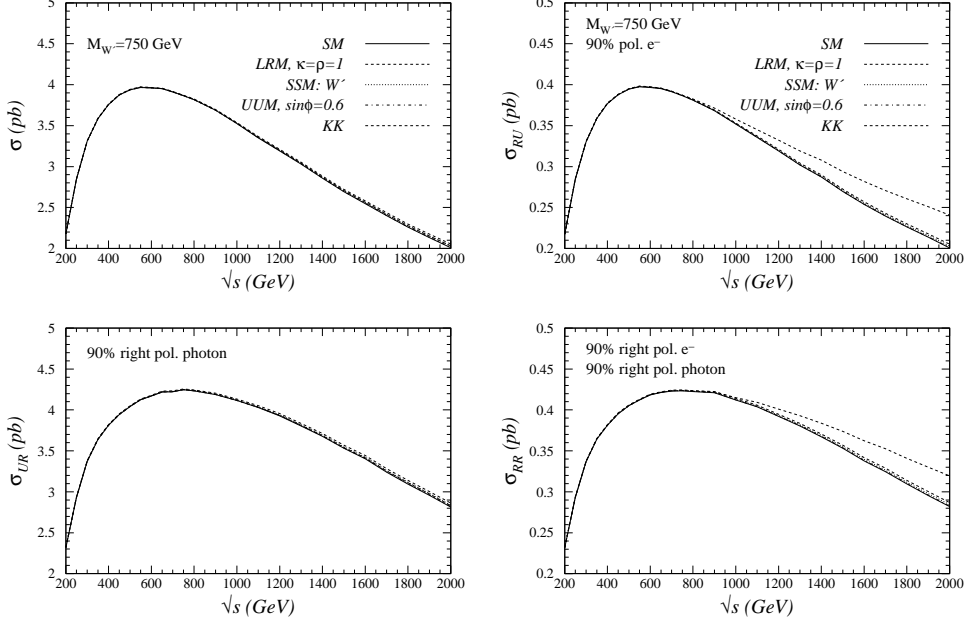
Fig. 2 *The total crosss sections* σ, σ_{RU}, σ_{UR} *and* σ_{RR} *as a function of* $\sqrt{s}$ *for* $M_{W'} = 750\,GeV$. *If polarized, 90% polarization of the electron and photon beams is assumed. Results are given for the SM (solid line), LRM (dashed line), SSM (dotted line), UUM (dash-dotted line) and the KK model (thick dashed line).*

$e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$ remains much less sensitive to a W' than the process $e^-e^+ \to \nu\bar{\nu}\gamma$. Sensitivity to models with a right-handed W' could be enhanced with higher degrees of polarization, of course, since the SM contribution vanishes for 100% right-polarized electrons. Left-handed electrons or photons give a sensitivity which is not better than that for unpolarized beams.

Figures 3 and 4 show the angular and energy distributions of the muon for different models. For the SSM W'_R, only the W'_R contribution is shown, for illustration. Compared to the total cross sections, the distributions give no enhancement in the sensitivity. (A lighter W' would give a larger signal.) A W' of 1.5 TeV *does* produce a signal in $e^+e^- \to \nu\bar{\nu}\gamma$.[4] In our process however, the SM and SSM lines are indistinguishable. Their difference is much below a reasonable systematic error of about 2%. The prediction for the SSM W'_R is different from the SM but it is suppressed by a factor of more than 10^5 as there is no interference with the SM. Even in the case of 100% right-polarized electrons, there would be only a few events. For realistic degrees of polarization, these events are contaminated by hundreds of thousands of SM events coming from left-handed electrons.

We see from figure 3 that the muonic angular distribution is strongly peaked in the direction of the photon (note the logarithmic scale). This indicates that diagram 2 in figure 1, where the muon is exchanged in the t channel, dominates the process.
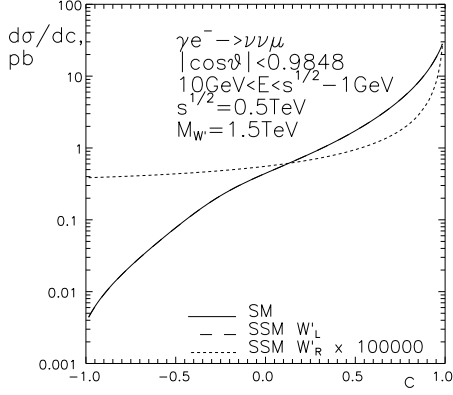
Fig. 3 *The angular distribution $d\sigma/dc$ for $\sqrt{s} = 0.5\,TeV$ and $M_{W'} = 1.5\,TeV$. Shown are the results for the SM (solid line), the SM with a left W' (long dashed line) and a right W' alone (short dashed line).*

Fig. 4 *The Energy distribution $d\sigma/dE$ for $\sqrt{s} = 0.5\,TeV$ and $M_{W'} = 1.5\,TeV$. Shown are the results for the SM (solid line), the SM with a left W' (long dashed line) and a right W' alone (short dashed line).*
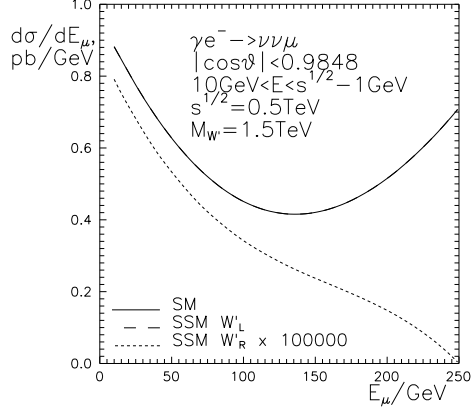
In this diagram, the charged gauge boson is also exchanged in the t channel. The corresponding propagator is largest for the ν_e travelling down the beam pipe. In this case, the propagator can be simply replaced by $1/M_W^2$ or $1/M_{W'}^2$. The exchange of the light SM W gives many events which contaminate a potential W' signal. In rough approximation, the fractional deviation from the SM cross section due to a left-handed W' is

$$[\sigma(SM + W') - \sigma(SM)]/\sigma(SM) \approx M_W^2/M_{W'}^2. \qquad (10)$$

For $M_{W'} = 1.5\,TeV$, this leads to a deviation of 0.3%. For a right-handed W', the deviation is proportional to the square of (10), as there is no interference with the SM. Consequently, the sensitivity to W''s below threshold is rather poor. As we go to higher energy, the sensitivity increases due to the larger phase space for neutrinos, which are not peaked along the beam pipe. Hence there will be an additional s-dependence in the deviation estimated in equation (10).

Let us remark about why the process $e^+e^- \to \nu\bar{\nu}\gamma$ is much more sensitive to a W' than the process $e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$. There are two clear reasons why $e^+e^- \to \nu\bar{\nu}\gamma$ is more sensitive. First, there is an interference between the W' and the SM Z for right-handed (and left-handed) W''s. Second, the majority of the events come from regions in the angular phase space where we are most sensitive to a W'. In $e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-$, the opposite is true as can be seen from figure 3. Even in the region where the relative deviation from the SM is largest, the effect of the left-handed W' is quite small and that of the right-handed W' is negligible (because the huge SM background contaminates a potential signal).

Similar arguments could be repeated for the processes $e^-\gamma \to d\bar{u}\nu_e$ and $e^-\gamma \to f\bar{f}e^-$, leading to the conclusion that these processes are also much less sensitive to a

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W' or Z' than $e^+e^- \to \nu\bar{\nu}\gamma$ or $e^+e^- \to f\bar{f}$. We finally conclude that the considered processes in $e^-\gamma$ collisions are not competitive to those in e^+e^- collisions in putting limits on four fermion contact interactions either.

1. G. Couture, S. Godfrey, P. Kalyniak, Phys. Lett.**B218** (1989) 361;
   G. Couture, S. Godfrey, P. Kalyniak, Phys. Rev. **D42** (1990) 1841.
2. J. Hewett; in *New Directions for High-Energy Physics: Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics*, Snowmass, Colorado, 1996, edited by D.G. Cassel, L. Trindle Gennari, and R.H. Siemann (Stanford Linear Accelerator Center, 1997), p. 887, hep-ph/9704292.
3. S. Godfrey, P. Kalyniak, B. Kamal, and A. Leike; in *Proceedings of MRST'99: High Energy Physics at the Millennium*, Ottawa, Canada, 1999, edited by P. Kalyniak, S. Godfrey, and B. Kamal (AIP, 1999), p. 1, hep-ph/9907571;
   S. Godfrey, P. Kalyniak, B. Kamal, and A. Leike; presented at *The International Workshop on Physics and Detectors at the Linear Collider*, Sitges, Spain, 1999, hep-ph/9909422. To appear in proceedings;
   S. Godfrey, P. Kalyniak, B. Kamal, A. Leike, hep-ph/9912444, LC note of the ECFA DESY Linear Collider Workshop, LC-TH-1999-022.
4. S. Godfrey, P. Kalyniak, B. Kamal, A. Leike, hep-ph/0001074.
5. J.A.M. Vermaseren, *Symbolic Manipulation with FORM* (CAN, Amsterdam, 1991).
6. F.A. Berends and W. Giele, Nucl. Phys. **B294** (1987) 700.
7. P.A. Baikov et al., Physical Results by means of CompHEP, in Proc.of X Workshop on High Energy Physics and Quantum Field Theory (QFTHEP-95), ed.by B.Levtchenko, V.Savrin, Moscow, 1996, p.101, hep-ph/9701412;
   E.E. Boos, M.N. Dubinin, V.A. Ilyin, A.E. Pukhov, V.I. Savrin, hep-ph/9503280.